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Time and position resolution of the scintillator strips for a muon system at future colliders

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ABSTRACT

Prototype scintillator+WLS strips with SiPM readout for a muon system at future colliders were tested for light yield, time resolution and position resolution. Depending on the configuration, light yield of up to 36 photoelectrons per muon per SiPM has been observed, as well as time resolution of 0.45 ns and position resolution along the strip of 7.7 cm.

1. Introduction

Several concepts of future colliders, including e^+e^- colliders, are currently under study for the next generation of particle physics experiments [1–4]. Due to the well-defined initial state of the interactions, low backgrounds and radiation levels, e^+e^- colliders are an attractive option for precision measurements to test various theoretical extensions of the Standard Model in the areas where the predictions of the beyond Standard Model theories differ by a few percent, such as in the Higgs sector.

The detector concepts for the future e^+e^- colliders have been developed to a high level of detail over the past decade. Since the publication of the Letters of Intent of the two major concepts, the Silicon Detector (SiD) [5] and the International Large Detector (ILD) [6], numerous technical details have been specified to an advanced level. R&D prototypes of individual subsystems reach levels of complexity involving hundreds of thousands of readout channels (see e.g. Refs. [7,8]).

However, for the muon systems relatively few specific details are developed, and few experimental tests of detection technologies have been performed. The muon system is envisioned as several layers of position-sensitive detectors embedded in the iron flux-return yoke of the solenoidal magnet. The role of the muon system at an e^+e^- collider is primarily the identification of muons and track matching to the central tracker, besides serving as the tail catcher for the hadronic showers that penetrate beyond the hadron calorimetry. Examples of previous experimental studies dedicated to the muon-system include tests of a similar detection technique as presented here, but focusing on light yield and attenuation [9], and beam tests of a multi-layer prototype devoted to a study of the improvement of energy resolution of a hadronic calorimeter by using the muon system as tail catcher [10]. The analog hadronic calorimeter developed and prototyped by the CALICE collaboration uses square scintillator tiles in sizes ranging from $3 \times 3\ \mathrm{cm}^2$ to $12 \times 12\ \mathrm{cm}^2$ with WLS fibers and SiPM readout with the aim of reconstructing the hadronic showers with optimal energy resolution [11]. A detailed study of the detection technique similar to the one presented here, focusing on light yield and attenuation for excellent MIP detection efficiency in very long strips for long-baseline neutrino detectors is presented in Ref. [12].

The achievable precision of track matching is limited by the multiple scattering in the detector components before the muon system. The effect of the multiple scattering on track matching can be estimated using the formula by Highland [13]. The total thickness of material in the radial direction between the central tracker and the muon system corresponds to about 150–300 radiation lengths, depending on the polar angle. Muons in jets, if they have sufficient p_T to reach the muon system, typically have energies below 10 GeV. Muon spectrum in the process $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ is shown in Fig. 1 as an example. At such energies, the contribution of the multiple scattering to the smearing of the muon system track position at the first muon-system layer is 5 cm or more.

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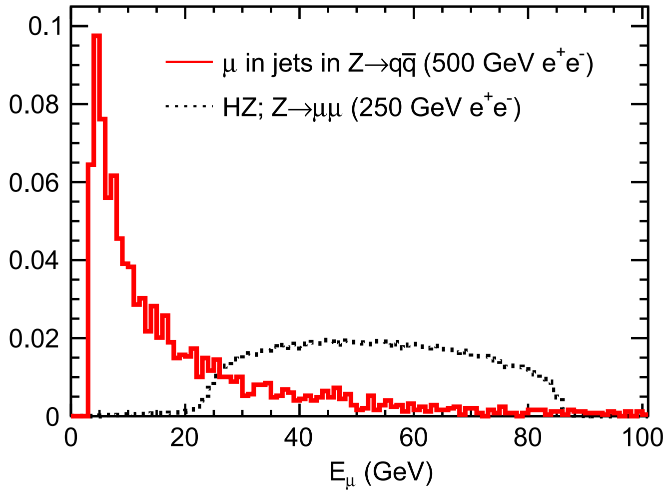

Fig. 1. Muon energy distribution for muons with sufficient p_T to reach the muon system. Solid line: muons in jets in the $e^+e^- \to Z \to q\bar{q}$ process at a 500 GeV e^+e^- collider. Dashed line: muons from the $Z \to \mu\mu$ decay in the Higgsstrahlung process at a 250 GeV e^+e^- collider.

Tracks of higher-energy muons, such as those coming from $Z \to \mu\mu$ decay, are less disturbed by the multiple scattering. Such relatively isolated muons are, however, less challenging for track matching in comparison to muons in jets. Fig. 1 shows the example of energy distribution of muons from the Z boson decay in the Higgsstrahlung process at a 250 GeV e^+e^- collider.

The total area of the muon detectors to be instrumented with sensitive layers is several thousand square meters. Besides, the iron yoke presents an environment difficult to access for maintenance. For these reasons, economic solutions for a robust and reliable large-area detector are important.

Occupancies in the muon system are moderate at e^+e^- colliders, except in the endcap region of a CLIC collider [14]. This allows us to consider a strip geometry for the sensitive layers in order to limit the number of readout channels. A promising option consists of scintillator strips with WLS fibers and SiPM readout [15]. In such a system, the coordinates of the muon track are reconstructed using the observables such as the position of the strip hit by a passing muon and the signal time difference Δt between the ends of the strip to measure position along the strip. If a muon system has strip orientations alternating by 90° in neighboring layers, the muon track can be reconstructed using only the positions of the strips that fired. In this case, the measurement of the position along each strip using Δt may serve to improve the precision of the track fit and to resolve “ghosts” arising at the intersections of strips hit by different particles. In the case when perpendicular orientation of strips is not feasible for access to the ends of the strips, time difference remains the only source of information on longitudinal position.

This paper is the first in a series devoted to the study of the time resolution and the position resolution achievable from the time difference between the ends of scintillator strips with WLS fibers and SiPM readout. The measurements described in this paper have been performed using cosmic muons at the location of the DØ assembly building at the Fermi National Accelerator Laboratory, Batavia, USA, at the elevation of 220 m above sea level. The local cosmic muon fluence has been measured previously by the MicroBooNE collaboration to be $\sim$100 $m^{-2}\,s^{-1}$, with a peak energy between 1 and 2 GeV [16].

Hamamatsu S10931-050P SiPMs with a sensitive area of 3×3 mm^2 and 3600 pixels each were used for the tests [17]. Various scintillators and fibers were used as described below.

Section 2 describes the measurement setup, Section 3 describes the amplitude and cross-talk calibration, Section 4 describes the tested scintillator strip – WLS fiber configurations, Section 5 gives details of the data analysis, in Section 6 measurement results are given and the conclusions are given in Section 7.

2. Measurement setup

The setup that was used for the measurements is shown in Fig. 2. It was designed to detect cosmic muons by coincidence between vertically arranged scintillation counters. S1 and S2 are plastic scintillation counters located above and below the tested strip, each of them 1 m long, 10 cm wide and 1 cm thick. S3 is a 1 cm thick scintillation counter with an area of 10×15 cm, oriented with its 10 cm side along the tested strip located at 6 cm vertical distance from the tested strip. S4 is a 40 cm long, 2.7 cm wide and 1.2 cm thick scintillation counter oriented across the tested strip and located at 2 cm vertical distance from the tested strip. The counters S1-4 were read out using vacuum photomultiplier tubes (PMT). SiPM1 and SiPM2 denote the SiPMs connected to the respective ends of the WLS fiber of the tested strip. The length of the tested strips is 1 m.

Coincidence between S1, S2 and S3 was used as the trigger, signalling the passage of a muon. The signal from S3 was delayed by 20 ns with respect to the signals from S1 and S2, so that the trigger signal is always formed at the rising edge of the S3 signal.

The counters S3 and S4 were used to restrict the location of the muon to an area smaller than the expected position resolution of the tested strip. The location of S3 and S4 along the tested strip was changed from run to run, keeping the relative position of S3 and S4 always the same. The distance from the axis of the tested strip to the PMTs of S3 and S4 was kept constant to ensure a stable time reference for the measurement of the time resolution of the tested strip. The reason for using two counters for the location restriction was the yet unknown resolution of the tested strips. The counter S4 provided precise location at the cost of slow

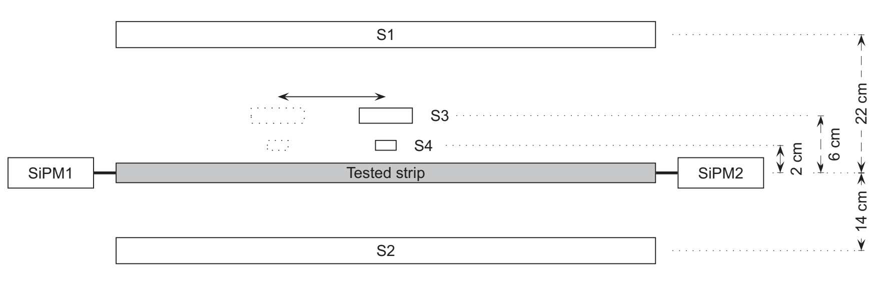

Fig. 2. Schematic of the test setup. S1 and S2 are scintillation counters with vacuum PMTs positioned above and below the tested strip. S3 and S4 are small-area scintillators with vacuum PMT used to select events where the muon hits specific location along the tested strip. The location of S3 and S4 w.r.t. the tested strip was changed from run to run, keeping the relative position of S3 and S4 always the same. SiPM1 and SiPM2 represent the SiPMs connected to the respective ends of the WLS fibers of the tested strip.